

and Industrial Automation subjects in Engineering Degrees

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Abstract—Engineering studies are usually based on mathematical, scientific and technical concepts. The use of these concepts in a practical way helps students to secure and assimilate them. The work presented in this paper includes the development of an economic training equipment for its use in the practical sessions of Automatic Control Systems and Industrial Automation subjects of the Undergraduate Degree in Industrial Electronic Engineering of the authors' university. The training equipment is based on a motorized linear axis. It can be controlled by a PC or a PLC. The equipment is very flexible and can be used for modelling or control training, allowing the emulation of different physical systems.

Keywords— *Automatic Control Systems, Industrial Automation, Training Equipment, Industrial Engineering.*

I. INTRODUCTION

In the scope of the “*Escuela Politecnica Superior*” of the University of Seville, Industrial Automation and Automatic Control Systems are common subjects for all Industrial Engineering degrees.

These subjects share a common conceptual scheme but, sometimes, this is not easily perceived by the students. However, Programmable Logic Controllers (PLCs), which are the base of the current industrial automation, are widely used to implement control loops in the industry [1]. Traditionally, control systems were implemented using discrete devices but nowadays thanks to the proliferation of PLCs, the reduction of their costs and the support of libraries given by manufacturers, the use of these systems has become a de facto standard [2]. Due to this, it is important to highlight to students the relationship between these two subject: Industrial Automation and Automatic Control Systems. Furthermore, the implementation of control loops on discrete systems as PLCs has certain implications and considerations that must be taken into account to guarantee the proper operation and stability.

Additionally, the theoretical concepts taught in these subjects are, sometimes, difficult to assimilate by students. Based on this situation, laboratory sessions in which students apply the concepts learnt in theoretical sessions have proved to be an efficient way to acquire and understand these concepts easier [3]. Moreover, practical sessions enhance the ability to work as a team and to follow complex instructions accurately [4].

In this sense, in the field of these subjects, there is a significant lack of affordable training equipment for the adjustment of control loops using PLCs. The available training devices are bulky and expensive, which makes it impossible to have one of these equipment for each student in laboratory sessions.

Due to that, there are generally not many platforms of this type available in the teaching laboratories. The few available devices are typically used for demonstration and verification purposes not being possible to carry out individual practices.

Having these facts, the use of simulators which emulates real facilities in practice sessions is common. But these simulators are generally simple and do not consider typical phenomena in real processes such as noise, limits of operations, nonlinearities, etc. Normally these simulators do not take into account these parameters because there are difficult to understand if no real equipment is available to observe them.

Based on this situation, people are developing their own training equipments for laboratory sessions [5] which may result cheaper and more convenient than equipments available in the market [6].

Due to this, this paper presents a new didactic equipment to be commonly available to the cited subjects. The proposed equipment is meant to be used for implementing positioning and speed control loops.

II. REQUIREMENTS AND CONCEPTUAL DESIGN

First of all, the requirements and objectives of the training equipment must be defined. Having the depicted problem with the existing material available in the market, the device must achieve two main requirements: A) Inexpensive. It must have a low fabrication price, allowing the possibility of having one of them for each student workstation. B) It must allow its use with PLCs as well as with a standard PC, allowing its use by students that may not have knowledge of PLC programming.

Having these requirements, training equipment for positioning and speed control loops has been designed. All the components used are based on COTS (Commercial Off-The-Shelf) components, making it affordable and easy to build and repair.

A conceptual scheme of the proposed training equipment is shown in Figure 1.

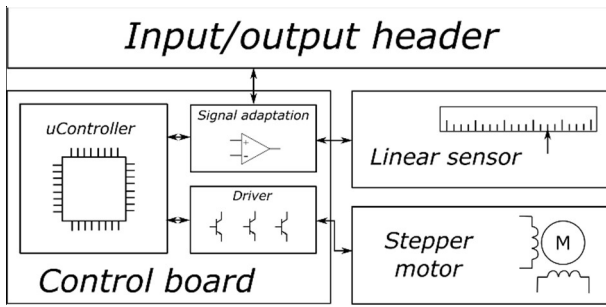


Fig. 1. Conceptual schema of the proposed training equipment.

The proposed equipment is conceived to be used for the training of position and velocity control loops. Therefore, the proposed equipment will act in a control loop as shown in Figure 2.

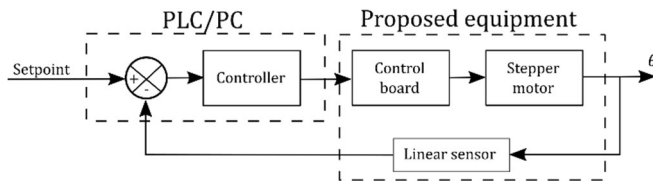


Fig. 2. Conceptual control loop using the proposed training equipment.

As it can be seen, the proposed device is based on three main components:

- A Motor, which acts as the actuator of the control loop. The motor will be based on a stepper motor but it has to emulate the behaviour of a standard DC motor.
- A linear sensor, which acts as the feedback of the control loop. It is based on variable resistor.
- A control board which has a microcontroller as well as all the necessary electronics.

The circular motor movement has to be converted into linear in order to allow both the position and speed control. In addition, as the actuator is based on a stepper motor, in order to provide a more complex and realistic position and speed control loops, the microcontroller will drive the stepper motor emulating a DC motor. Having this schema, different dynamics could be implemented. This emulation may be seen as a contradiction with the statements made in the introduction about the use of simulators. But, it needs to be said, that even an emulation of a DC motor is performed, the device does not pretend to be a simulator of a DC motor. The device pretends to be a physical equipment in which students could directly see effects like overshooting, steady state error, etc.

Additionally, the microcontroller together with the dedicated electronics will also be responsible for acquiring and adapting the different signals coming to and from the training equipment. Furthermore, the microcontroller will be responsible for guaranteeing the security of the system regardless of the orders received.

Signals to and from the system need to be available both on an USB interface and on a physical header. This will allow the system to be connected directly to a PC, or to an external control device, as a PLC, enabling the training of the students not only using PLCs but also using PCs.

III. TRAINING EQUIPMENT DESCRIPTION

Having a first draft of the proposed equipment, a prototype has been manufactured and tested. The prototype is shown in Figures 3 and 4. Figure 3 shows the front user panel and Figure 4 the back panel with the connections and control board.

The prototype has been manufactured using a laser cut methacrylate panel and 3D modelled pieces.

Automatic or manual modes are available. With the switch in manual mode, the actuator can be positioned in any location using the available buttons. When the device is in automatic mode and no USB is connected, the equipment is managed by means of the header signals. When the USB is connected the control can be done by the signals coming from the PC.

Two physical limit switches are placed on the end positions of the rack to restrict the movement.

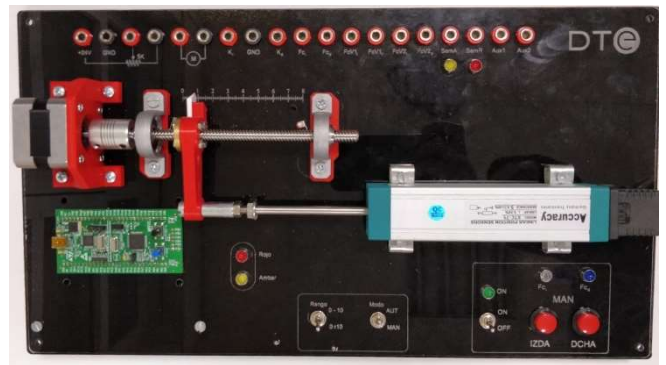


Fig. 3. Front panel of the proposed training equipment.

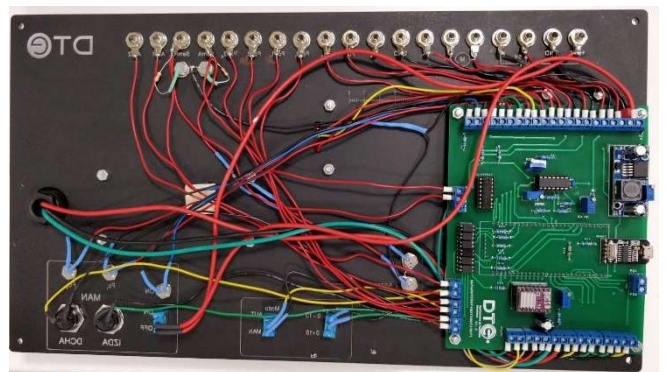


Fig. 4. Back of the proposed training equipment.

A. User panel description

As it can be seen in Figure 3, the proposed training equipment has three different parts: a header, the device under control and the switches and buttons for the user.

The device under control is a stepper motor which can be controlled both in position or velocity. The motor is coupled to an worm screw. The worm screw has a tip which moves in one direction or another based on the circular movement of the motor. In order to visually confirm the position of the tip, a ruler has been printed on the panel. The tip is coupled to a variable resistor which acts as a linear sensor and the feedback of the control loop.

The user buttons and switches allow the selection between automatic and manual modes. In manual mode, the motor can be positioned using the available buttons on the panel or using external signals available on the header. In addition, the user

can select two different ranges of the analog inputs/outputs: 0-10V or +-10V.

Indication LEDs are also available in the user panel to indicate limit positions or mark unsafe situations.

B. Signals available in the header

In order to control the device, all signals from and to the board are available on a header. This header has the following signals:

- Power input. The device must be externally powered by a 24V power supply.
- Linear sensor output. Analog value of the cursor of the variable resistor.
- Motor setpoint. Analog input which controls the stepper motor velocity.
- On/off control mode inputs. In addition to the analog setpoint, the motor can be controlled using two on/off inputs, one for each direction.
- Limit switches. Both limit switches outputs are available as external signals.
- Virtual limit switches outputs. Two virtual limit switches can be defined by means of the USB interface.
- Expansion inputs/outputs. Two additional inputs/outputs have been reserved for future applications.

The motor can be controlled using the analog motor setpoint input or the on/off inputs. On automatic mode the device gets the setpoint from the analog input. Conversely, on the manual mode, the device is controlled using the on/off digital inputs.

As it was mentioned before, all analog signals are operable under 0-10V and +-10V ranges in order to be used with industrial equipment such as PLCs. In the same way, digital signals work with industrial range 0-24V.

C. Control board description

The control board has a microcontroller, an USB interface and the electronics to drive the motor and to acquire and process the signals of the board.

In this sense, inputs and outputs are converted to the desired industrial values: 0-10V or +-10 for the analog signals and 0-24V for the digital signals.

Furthermore, the microcontroller is responsible for implementing the dynamics of the system. As it was said before, the system is meant to emulate the behaviour of a DC motor, this is done by the microcontroller which acquire the motor setpoint and acts over the motor drivers. This behaviour will be described in Subsection IV.

Having this configuration, it is easy to implement different dynamics having the same equipment, avoiding cheating among students.

Moreover, invalid signals or unsafe situations are also handled by the microcontroller.

In addition, the microcontroller manages the USB interface with which the system can be also controlled by means of a PC.

Two main control modes are available: automatic and manual. In manual mode the motor can be positioned using the available user buttons or by means of the inputs of the header. This mode is used by the user to position the device in a certain location or for implementing on/off controls using PLCs. In this sense, the device could be used not only for the implementation of control loops but also for PLC trainings using DES (Discrete Event System) models. In automatic mode, the motor velocity is controlled by means of the analog setpoint input of the board. The velocity is controlled using 0-10V or +-10V depending on the configuration. In this mode, the control loops using PIDs could be implemented.

D. USB interface.

Thanks to the provided interface, the board can be fully configurable and controlled. For that purpose, an API with a MATLAB connector has been developed. This control is done by means of the USB interface.

Three main functions are available:

- Receive data from the board. The board is continuously sending the parameters acquired such as: current position, input voltage, etc.
- Send data to the board. The input header is simulated using this function. In this sense, the device can be fully controlled using the USB interface.
- Configure parameters. The system behaviour can be parametrized through this interface. This will be extended in the next section.

E. Cost analysis.

One essential factor throughout the design of the proposed device was the cost, trying to obtain a device with an acceptable value to have one per student's workstation.

For that purpose, COTS elements have been used in the design, allowing the reduction of the price and being easy to repair. Even the control board has been made using COTS when possible.

Table 1 shows the price of the prototype as well as the detailed description of the different parts that involves the construction of it. It is important to highlight that the indicated prices are for a short run. Having larger runs would make the system cheaper.

TABLE I. COST DETAIL FOR THE PROPOSED EQUIPMENT

Part	Notes	Price
Stepper motor	Actuator of the control loop	8.20€
Linear sensor	Feedback of the control loop	25.30€
Control board	Includes all the necessary electronics	40€
Mechanic parts	Worn screw, bearings, etc.	18.60€
3D printing parts	For mechanical fastening	4€
Methacrylate panel	For the user panel	11.60€
Assembly	Assembly of the materials by a technician.	50€
Others	Buttons, LEDs, terminals, cables, etc.	15€
Total		172.7€

IV. DYNAMIC MODELLING OF DC MOTOR

The actuator of the control loop is a stepper motor. However, as it was said before, the system is intended to be controlled as a DC motor.

Therefore, the microcontroller could be used to implement this behaviour and emulate a DC motor. For that purpose, the model of the DC motor must be known. Thus, in this section the model that will be implemented in the microcontroller will be obtained, so that seen from the PLC/PC, the system behaves like a DC motor.

Thus, the electric model of a permanent magnet DC motor is shown in Figure 5.

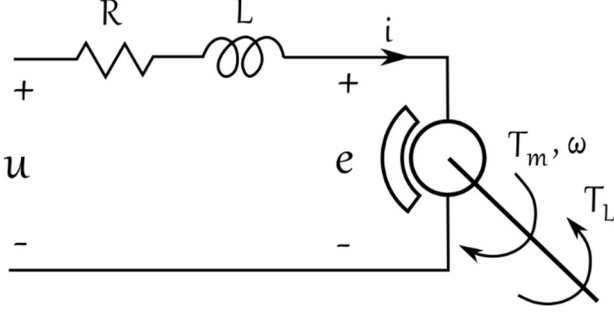


Fig. 5. Back of the proposed training equipment.

Where U is the voltage at the motor terminals, R the resistance of the armature circuit, L the inductance of the armature circuit, i the current of the armature, e is the back electromotive force (EMF), T_m is the motor torque, ω the velocity of the motor shaft and T_L is the torque of the load.

This model can be described with three kinds of equations: electric, electromechanical and mechanic.

First of all, the electric equations can be obtained from the schematic shown in Figure 5:

$$u = iR + L \frac{di}{dt} + e \quad (1)$$

Secondly, as we know, the motor torque is directly proportional to the armature current and the back EMF is directly proportional to the shaft velocity. Therefore, equations (2) and (3) are obtained.

$$T_m = K_T i \quad (2)$$

$$e = K_V \omega \quad (3)$$

Where K_T is the torque constant and K_V is the velocity constant. If the motor wasn't based on permanent magnets, these wouldn't be constants as the relation between torque and current depends on the flux as well as the relation of EMF and velocity. But, in this case, the flux is constant thanks to the permanent magnets so the relation between these variables is constant.

Finally, if the inertia and the friction of both of the motor and the load is considered, the mechanical equation (4) is obtained.

$$J \frac{d^2 \theta}{dt^2} + B \frac{d\theta}{dt} = T_m - T_L \quad (4)$$

Where J is the inertia, B the friction and θ the position of the shaft.

In order to implement positioning or velocity control, the transfer function between the input voltage and the shaft position must be obtained with the depicted equations. Thus, if (1), (2), (3) and (4) are given in the Laplace domain:

$$U = IR + LIs + E \quad (5)$$

$$T_m = K_T I \quad (6)$$

$$E = K_V \theta s \quad (7)$$

$$J\theta s^2 + B\theta s = T_m - T_L \quad (8)$$

Operating on (5), to leave current and substituting on (6) the next equation can be obtained.

$$T_m = K_T \frac{U-E}{R+Ls} \quad (9)$$

With (9) and (8).

$$J\theta s^2 + B\theta s = K_T \frac{U-E}{R+Ls} - T_L \quad (10)$$

Operating on (10) and using (7).

$$\theta s((Js + B)(R + Ls) + K_V K_T) = K_T U - T_L(R + Ls) \quad (11)$$

Obtaining the position from equation (11).

$$\theta = \frac{K_T U - T_L(R + Ls)}{s((Js + B)(R + Ls) + K_V K_T)} \quad (11)$$

As can be seen, the position is dependent on the input voltage and on the torque load. Applying the superposition principle, the position model can be decomposed on (13) and (14) transfer functions.

$$\theta = f(U, T_L) \quad (12)$$

$$\frac{\theta}{U} = \frac{K_T}{s((Js + B)(R + Ls) + K_V K_T)} \quad (13)$$

$$\frac{\theta}{T_L} = \frac{-T_L(R + Ls)}{s((Js + B)(R + Ls) + K_V K_T)} \quad (14)$$

Thus, the DC motor model can be expressed as function blocks as it is shown in Figure 6.

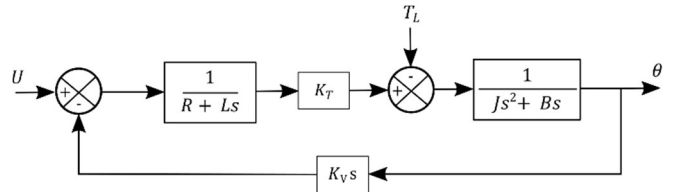


Fig. 6. DC motor position block model.

Additionally, the velocity can be obtained derived from the position. In the Laplace domain, this means multiplying by s . Thus, the velocity model can also be obtained (Figure 7).

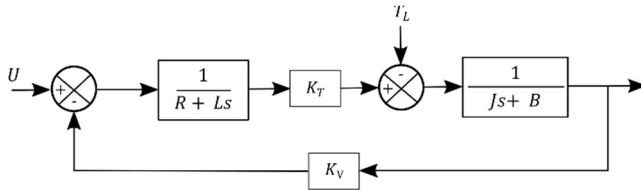


Fig. 7. DC motor velocity block model.

Considering that the torque load is constant for the described equipment and that the armature inductance is negligible on the majority of available DC motors, the models can be simplified as shown in Figure 8 and 9.

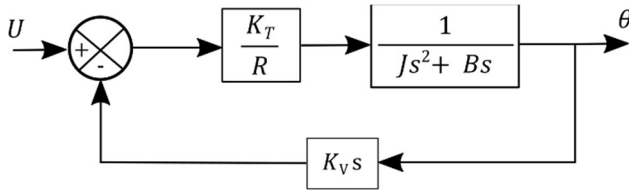


Fig. 8. Simplified DC motor position block model.

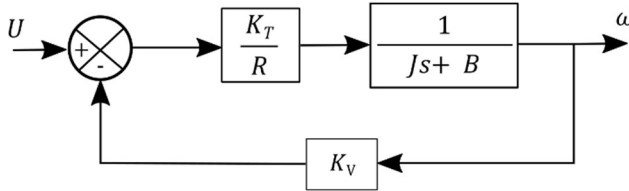


Fig. 9. Simplified DC motor velocity block model.

Thus, the model in position and velocity a permanent magnet DC motor it is shown in (15) and (16).

$$\frac{\theta}{U} = \frac{1}{s} \frac{K}{\tau s + 1} \quad (15)$$

$$\frac{\omega}{U} = \frac{K}{\tau s + 1} \quad (16)$$

Where $\tau = JR/(BR + K_T K_V)$ and $K = K_T/(BR + K_T K_V)$.

As can be seen, the model of a permanent magnet DC motor is a first order transfer function. Taking in to account that the actuator in the proposed training equipment is a stepper motor, the microcontroller will be responsible for implementing this model.

In addition, in order to give more realism to the system, a delay has been added to the system. Thus, the model implemented in the microcontroller is:

$$\frac{\omega}{U} = \frac{K e^{-Ds}}{\tau s + 1} \quad (17)$$

Where D is the delay of the system. Thus, the system under control will be as shown in Figure 10. For the user, the system will act as a standard DC motor.

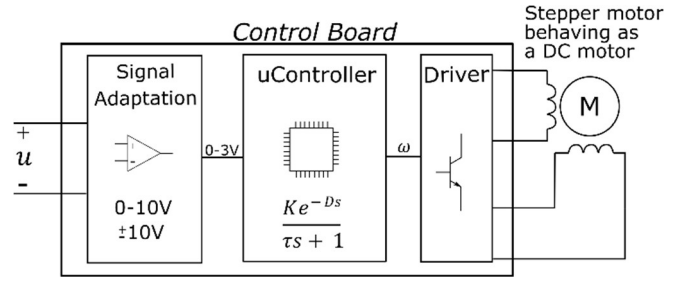


Fig. 10. DC motor position block model.

This schema gives one important feature for training: the same device could behave differently. Thus, every student could have a different model to control avoiding cheating on exams.

The configuration of the model parameters can be uploaded to the board by the teacher connecting the board to a PC using USB interface. A program specifically made for that purpose has been developed (Figure 11). Using this interface, the parameters can be uploaded to the board. In addition, the device can also be tested.

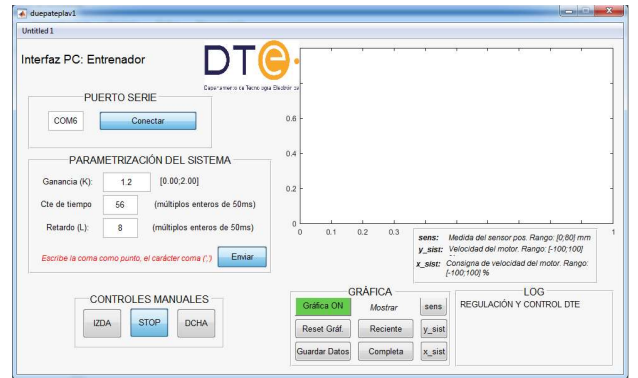


Fig. 11. Teacher interface used to configure the model parameters.

This interface will be used by the teachers to individually set the parameters of the device. This is especially interesting for avoiding cheating.

V. TRAINING SCENARIOS

Based on the described characteristics, the proposed equipment can be used in laboratory sessions practices. Two main control scenarios can be applied to the proposed equipment: positioning control and velocity control. For positioning control, a second order model needs to be controlled. Conversely, for velocity control, a first order model has to controlled.

The board can be interfaced in two different ways: using digital signals or analog signals. These two approaches are described in subsections A) and B).

In addition to the control based teaching sessions, other kinds of practice sessions could also be conducted using the proposed equipment. For example, for system modelling as it will be described in subsection C) or for PLC basic training as shown in D).

A. Discrete control

In addition to the control of the motor in an analog way through the input voltage, the motor can also be controlled in a discrete way by means of two available inputs: one for each

direction. In this way, a discrete two-point control will be done by means of two digital outputs of the PLC.

The digital signals coming from the PLC will be converted to a constant velocity setpoint on one direction or another by the microcontroller which will act over the motor driver.

In addition, as it was described before, this control could not only be done using PLCs but also using MATLAB in a PC. In this sense, the training equipment can also be used for students that aren't familiar with PLC programming. This is especially useful for some grades in which the subject Automatic Control Systems is taught before than Industrial Automation.

B. Analog control

Conversely, to the previous scenario, an analog control of the motor input can also be done. In this scenario, the input will be controlled by an analog output of the PLC.

As well as the previous scenario, this control can also be done using the PC.

C. System modeling.

In order to obtain a controller for a certain system, the model must be known. For this purpose, the PC interface could be used to acquire data from the board and experimentally obtain the model of the system whose parameters are unknown for the students.

D. Others

In addition to the sessions related to the modelling and control of dynamic systems, the proposed device could also be used for PLC and microcontroller training.

For example, for basic DES training using PLCs, the control of a barrier could be implemented. One end represents the raised barrier and the other end the lowered barrier. Additionally, the virtual limit switches can be used to define different velocities depending on the position of the barrier.

In addition, as it was said, the equipment could also be used for microcontroller training. For example, implement different step motor kinds of control as micro stepping.

VI. CONCLUSIONS

This paper proposes training equipment to be used in practical sessions of Industrial Automatic Control Systems and Industrial Automation. These subjects are in the scope of the "Escuela Politecnica Superior" of the University of Seville.

A prototype of the proposed equipment has been manufactured and validated. Twelve devices are being manufactured and different practice sessions are being designed to be used in the cited subjects on the next academic course. These practices cover aspects as the modelling of dynamic systems, or the test of different open and closed control strategies with PLCs.

Even though no results have been obtained from its use in laboratory sessions since the device is expected to be used in the next academic, the device was given to intern students and some feedback have been obtained. Intern students state that the use of the proposed equipment helps them to assimilate better the concepts of both control loops and its integration with PLCs.

Until now, most of these aspects are covered theoretically or, due to the cost, with a reduced number of physical models. But the proposed equipment has a reduced cost, making it affordable to have one training equipment for every student's workstation in the lab. This can be done due to most of the components used in the training equipment are based on COTS (Commercial Off-The-Shelf) elements.

The use of this equipment will help students to understand and assimilate theoretical concepts better. Additionally, with this device, the relation between the cited subjects will be clearer to students.

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